Magnetic Studies of Rocks and Sediments Obtained by Deep Drilling[1]

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THE MAGNETIC PROPERTIES of the crustal materials which may be drilled in Project Mohole should have many points of geochemical interest. For example, the magnetic susceptibility, the Curie temperature, the magnetic hysteresis, and the magnetic anisotropy may reflect pressure, temperature, and chemical relationships in the crust and upper mantle. In addition, the rocks and sediments may be expected to have a remanent magnetism which has been acquired in the earth's field and may have paleomagnetic significance.

Inasmuch as the average heat flow value in the area of the proposed drilling site is normal, an average conductivity figure of 2×10^{-3} Cal/°C sec yields a thermal gradient value of 70°C/km. Thus, the depth to the magnetic Curie isotherm typical for oceanic basalts can be expected to lie more than 8 km below the surface of the sediments—too deep to be reached by the drilling operation. For most of the material encountered during drilling, we can therefore expect a remanent magnetism which is controlled by the cooling of the material through the Curie point as it formed, that is to say, a thermo-remanent magnetization. In the sediment overlying the crustal rock there may be such magnetizations produced by heating from below, but, in addition, there will be some sedimentary acquired magnetism. Previous work of the writer on exactly such material has shown that it may be of great importance to our understanding of past changes in the geomagnetic field.

Many workers have contributed to studies of ancient magnetizations in igneous rocks. In Hawaii, Doell and Cox (1961*a*) and Tarling and McDougall (1963) have made measurements of the magnetism remanent in several lava flows. The Hawaii Institute of Geophysics is preparing to extend such measurements during the coming year. To illustrate how studies such as this may give support to Project Mohole, we will discuss the studies made on material obtained by the trial drilling off Guadalupe in 1961 on the drilling barge "Cuss II."

In that operation drilling extended to 181 m beneath the sea floor. The final 11 m were drilled in a basaltic rock which was overlain by pelagic clays. The natural magnetic remanence of this basalt showed a reversed polarity and no detectable anisotropy was found in the magnetic susceptibility. Doell and Cox (1961*b*) have reported studies made on 23 specimens of this material. The writer worked on 5 samples taken from material between 100 and 110 cm into the basalt. These samples showed a high uniformity in direction of the natural magnetic remanence with only a ½° scatter in declination values and a 1½° scatter in the inclination. Three Curie temperature measurements were made on the material. All indicated a Curie point of 325°C ±10° (Fig. 1). There was no indication of a multiple Curie point pattern in any of the curves. One measurement was conducted under an astatic magnetometer so that the direction of the natural remanence could be observed as heating proceeded. This measurement showed no appreciable change in direction of the remanence as the temperature approached the Curie point.

The Curie point agreed well with petrological examinations of the sample. The rock was a fresh, medium grained, olivine basalt, quite rich in pyroxene. The color of the pyroxene suggested that the mineral was low in titanium, and that this element could therefore account for the low Curie temperature in the titano-magnetite mineral fraction. The petrological description of this rock given by Engel and Engel (1964) fitted well the samples which we examined.

Structural and petrological examination suggested that this basalt had been intruded under some cover of sediment. The amount of cover could not be readily ascertained. This suggested

[1] Hawaii Institute of Geophysics Contribution No. 101.

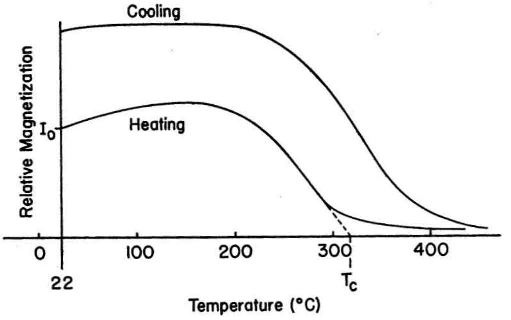

FIG. 1. Pyromagnetization curve established experimentally for the EM 7 basalt.

to us two primary experiments: first, to see if the overlying sediment had been heated sufficiently to acquire a thermo-remanent magnetization; and, second, to determine whether this thermo-remanent magnetization agreed in direction with that of the basalt. If it did so, this would be strong evidence that the whole event had taken place during the period when the main magnetic field of the earth was reversed in polarity from the sense that it has today.

A second study would be to extend the examination for thermo-remanence upward from the contact to see the manner in which it diminished with distance. If intrusion had occurred under a thick overburden, one could expect the thermo-remanent magnetization to give way to a partial thermo-remanent magnetization and the total effect to diminish in an exponential manner. On the other hand, if intrusion had occurred under a very thin overburden of sediment, then the heat pulse from the basalt might well have broken through to the sea floor and been dissipated before any appreciable thickness of sediment had been further deposited in the area. In this case, the upward change of thermal magnetizations would show a discontinuity, diminishing suddenly to the level common for sedimentary type magnetizations. The time scale over which such a cooling might take place and the extent to which temperature isotherms might extend from the basalt could be judged from studies made earlier by Jaeger (1957). Figure 2 is a diagram prepared from such considerations for the case where the overburden equals the thickness of an intruded sill. It may be seen from this that the 600° isotherm would extend outward to distances of about 20 per cent of the total thickness of the sill. Lower isotherms which could still produce an appreciable partial thermoremanence might extend out much farther, in excess of half the thickness of the sill. The cooling period would extend over several hundreds of years.

Studies of the sedimentary rock core above the basalt have been hampered for two reasons. First, recovery was very incomplete, particularly in the drill hole which penetrated through the basalt (EM 7). Second, the material was rich in calcareous ooze and had abnormally low magnetic properties as compared with other abyssal sediment. The material placed at our disposal for study was largely confined to Run 3 of the EM 7 drilling. Within this section we had 13 samples ranging from distances of 32 cm above the basalt upwards to a distance of 114 cm. The 6 lowest samples which ranged to distances of 58 cm from the contact showed a positive inclination. The 6 samples overlying this, ranging to a height of 113 cm, had a negative inclination paralleling quite closely that found in the basalt. One positive inclina-

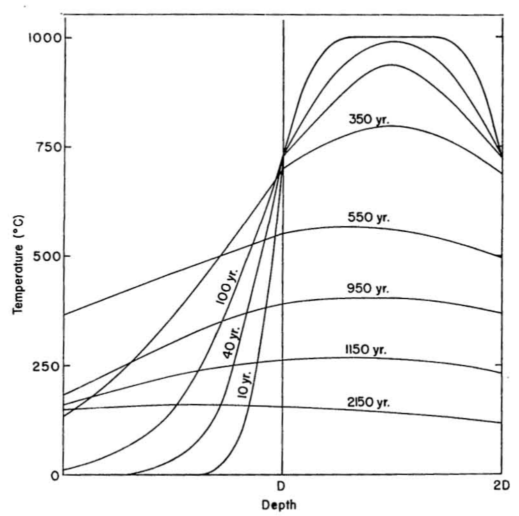

FIG. 2. Change of isothermal lines with time during the cooling of a thick intrusive body.

tion was obtained in the sample taken above this level. Thus, the material which was closest to the basalt and which should have been heated by it to produce a thermo-remanent magnetization in accordance with that of the basalt, did not show this effect.

This pattern of magnetic polarizations presents a paradox. The facts might be interpreted by three hypotheses: (1) The material nearest the basalt might have become unstable, or perhaps was altered by processes emanating from this igneous body, and acquired its field more recently. (2) The positive direction indicates a period of normal magnetizations which was typical of the time at which the basalt was intruded; subsequent to this, a period of reversal occurred during which the overlying reversed materials were laid down and exsolution products in the basalt caused the acquisition of a now reversed remanent magnetization. (3) The reversed magnetization of the basalt may be an example of a spontaneous self-reversal occurring during a period which is better documented by the positive inclination of the immediately overlying and thermally magnetized sedimentary material, remagnetized by the intrusion from its original reversed polarization which is still retained to within 1 m of the contact.

Even on the assumption that the basalt is but little thicker than the maximum depth to which it was penetrated by the drill, we cannot consider the sampling available sufficient to permit a conclusive study of the manner of decrease of thermo-remanent magnetizations away from the contact.

These studies indicate two points that should be taken into consideration in planning any later deep drilling operations. First, it is extremely important for these studies that some attempt be made to orient the core. The writer discussed this point at great length with people in the office of the AMSOC committee (of the Division of Earth Sciences, National Academy of Sciences) during the period of preparation in 1960 for the "Cuss II" operations. Unfortunately, the intent expressed then to orient all cores was not realized. Second, it is extremely important in studies of this type that recovery be as complete as possible, even in the sedimentary column.

A further matter for consideration has come from studies of these "Cuss II" drill samples. This concerns the consolidation characteristics and porosity of the sediment as studied and reported by Hamilton (1964) and by Moore (1964). Hamilton shows that porosities at the sediment surface were about 80 per cent and that *in situ* porosities for the deepest samples were of the order of 72 per cent. Thus, a reduction of no more than 5 per cent due to overburden pressures could be accounted for even in the deepest sample studies (168 m). Moore shows that the shear strength varied from less than 0.1 kg/cm^2 at the surface to more than 2.8 kg/cm^2 near the basalt.

These findings have two points of importance to studies of magnetism. First, the increase in shear strength seems to be due to diagenetic processes such as cementation and bonding. These processes might be important in the acquisition of chemical magnetizations during the consolidation history of marine sediment, particularly in an area where iron cementation might be expected. Second, these studies in no way support the suggestion made by Keen (1961), working with the writer at Cambridge University, that compaction might produce an inclination error which would increase with burial depth in samples taken by piston coring.

The deep marine magnetic studies being done by the Hawaii Institute of Geophysics, in addition to studies of Hawaiian basalt, should continue to have immediate relevance to the Moho Hole drilling project. Our measuring equipment and techniques are eminently suited to this task. One particular area to which we can contribute comes from the knowledge we have acquired in successfully constructing a photographic recording instrument which can orient a deep-sea sediment core.

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